Tuned Mass Dampers and Hybrid Vibration-Control Systems for High-Rise Buildings

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Abstract: ***High-rise buildings are dynamically sensitive to earthquake and wind actions because increasing flexibility, modal coupling and low inherent damping can amplify displacement, inter-storey drift and acceleration. This review synthesizes the design logic, performance evidence and implementation constraints of tuned mass dampers (TMDs) and related hybrid systems. A PRISMA 2020-compatible protocol is specified for Scopus, Web of Science, ScienceDirect, SpringerLink, ASCE Library and IEEE Xplore; numerical record counts are retained as explicit placeholders because database exports were not supplied. Ten DOI-identified studies published from 2021 to 2024 form the focused critical evidence set, supplemented by the uploaded dissertation only as thematic context. The synthesis distinguishes conventional and multiple TMDs, semi-active systems, tuned mass damper inerters, nonlinear energy sinks and base-isolation hybrids. Across this evidence, performance is controlled by mass ratio, frequency and damping ratios, device location, modal participation, excitation spectrum, structural nonlinearity and soil–structure interaction. Advanced systems can widen effective bandwidth or reduce physical mass, but may increase stroke, control force, sensing, maintenance and reliability demands. Numerical optimization dominates the literature, while comparable experimental and full-scale evidence remains limited. The review contributes a design-variable–response map, a hazard-sensitive comparison framework and a future roadmap integrating nonlinear analysis, uncertainty quantification, lifecycle cost, digital twins and long-term monitoring. No control system is universally superior; selection should be based on governing response, hazard, robustness, constructability and whole-life performance.***

Keywords: tuned mass damper; high-rise building; seismic control; wind response; inerter; base isolation; optimization; structural vibration

1. Introduction

Urbanization has changed the form and function of modern cities. Growth of population, concentration of commercial activities and scarcity of open land have increased the demand for vertical development. High-rise buildings are therefore adopted to accommodate residential, commercial and mixed-use requirements within limited plot areas. They make efficient use of urban land, support compact development and create the possibility of integrating offices, residences, parking, services and public amenities in one vertical system. However, the structural behaviour of such buildings is more complex than that of ordinary low-rise buildings because height, slenderness and flexibility increase the influence of lateral dynamic actions. A high-rise building behaves as a tall cantilever fixed at its base. As the height increases, lateral displacement and inter-storey drift become important design concerns. Gravity loads are still significant, but the governing design condition often shifts from vertical load carrying capacity to control of wind and earthquake response. Tall buildings are continuously exposed to wind pressure, gust effects, vortex shedding, seismic ground motion and vibrations generated by machines and occupants. If these actions are not properly controlled, they can cause excessive sway, cracking, discomfort, malfunctioning of non-structural components and reduction in the service life of the structure.

Traditional approaches for limiting vibration include increasing member sizes, adding shear walls, using braced frames or increasing overall stiffness. These methods improve resistance, but they also increase structural weight, foundation demand and construction cost. In modern tall buildings, where architectural openness, slender form and efficient material use are required, merely increasing stiffness is not always economical or practical. Hence, structural engineers increasingly use supplemental vibration-control systems that absorb or dissipate a part of the dynamic energy entering the structure.

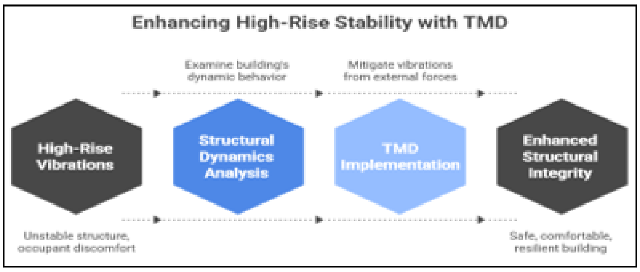

Figure 1: Enhancing High-Rise Stability with TMD

Tuned Mass Dampers (TMDs) are among the most effective passive vibration-control devices used in tall buildings. A TMD consists of a secondary mass connected to the main structure through a spring and damping mechanism. The mass is tuned to the dominant natural frequency of the building so that, when the building vibrates, the damper mass moves out of phase and produces an opposing inertial force. This reduces the amplitude of vibration, improves serviceability and increases comfort for occupants. Because the system is comparatively simple, reliable and suitable for installation at roof or mechanical levels, it has become an important solution for high-rise structures subjected to wind and seismic effects.

The present report deals with the analysis and design of a high-rise RCC building frame with a Tuned Mass Damper. A G+10 building is analysed by considering different structural configurations, including a basic model without control, a model with base isolation, a model with a roof-level TMD and

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a combined base isolation and TMD model. The response of the structure is evaluated mainly in terms of storey displacement, storey drift and base shear in both principal directions. The introduction chapter therefore explains the need for high-rise construction, the nature of dynamic loads, the role of vibration control and the working principles of TMD systems.

Tall and slender buildings derive efficiency from light, flexible structural systems, but the same attributes increase sensitivity to long-period ground motion, wind turbulence and vortex shedding. Structural safety is therefore only one design objective: peak and residual drift, non-structural damage, acceleration-sensitive contents and occupant comfort may govern different limit states. Supplemental vibration-control devices provide an alternative to increasing member size because they redirect or dissipate dynamic energy.

A conventional TMD comprises an auxiliary mass, spring and dissipative element tuned near a target structural frequency. Relative motion of the auxiliary mass produces an opposing inertial force and transfers energy away from the dominant mode. Its simplicity is attractive, yet narrow-band behaviour makes it vulnerable to detuning caused by cracked stiffness, soil flexibility, temperature, ageing or structural damage. Recent research therefore explores multiple, semi-active, inerter-based and hybrid arrangements. This review critically maps those developments and separates simulation efficiency from validated practical performance.

2. Literature Review

The first evidence cluster links retrofit feasibility, modal placement and adaptive or hybrid control. Read collectively, the five studies show a transition from single-response tuning toward constrained system design; each approximately 100-word critical abstract below preserves the study's scope and limitations.

Marrazzo et al. (2024) examined high-mass-ratio tuned mass dampers as a seismic-retrofit option for existing buildings. The study departs from the conventional assumption that the auxiliary mass must remain small and uses parametric dynamic analysis to relate mass ratio, damping and ground-motion demand to response control. Reported reductions in roof displacement and acceleration indicate that large auxiliary masses can be effective when architectural or retrofit constraints permit their integration. The contribution is practically important because it links damper sizing to retrofit performance rather than treating tuning as an isolated mathematical problem. Its transferability nevertheless depends on structural typology, available space, stroke capacity and the representativeness of the selected earthquake records. Akyürek (2023) compared height-wise placement strategies for multiple tuned mass dampers, distinguishing a first-mode-dominant arrangement from a multi-mode-control arrangement. The results show that placement cannot be separated from the response objective: configurations concentrated around dominant modal ordinates tend to control displacement and velocity, whereas distributed, mode-specific arrangements can improve acceleration control. This distinction is especially relevant to tall buildings, where occupant comfort and structural demand may be governed by different modes. The paper therefore supports response-specific design rather than a single universal location rule. Its principal limitation is that conclusions from idealized numerical models require verification under parameter uncertainty, nonlinear response and realistic installation constraints. Kim and Kang (2021) investigated a semi-active tuned mass damper for a tilted high-rise structure subjected to seismic excitation. Magnetorheological devices and a fuzzy-control strategy were used to vary the effective damping action, allowing the controller to respond to changing structural states. Comparison with passive and alternative semi-active schemes indicated that adaptive control can achieve useful vibration reduction with less auxiliary mass than a conventional passive TMD. The study is valuable for geometrically unusual towers, where gravity-induced bias and coupled response complicate fixed tuning. However, practical performance remains conditional on sensor quality, control latency, fail-safe behaviour, power continuity and actuator force limits, which should be incorporated in full-scale qualification. Yue and Han (2024) developed a multi-objective design framework for a tuned mass damper inerter coupled to a base-isolated structure. Instead of optimizing structural response alone, the formulation balances response suppression against control force, a quantity that directly affects connections and inerter hardware. Their eight-storey validation example and non-stationary excitation assessment show why a Pareto solution is more informative than a single optimum. The paper also accounts for nonlinear isolation through a Bouc-Wen representation. Its main contribution is the explicit recognition that stronger apparent inertia may reduce motion while increasing transmitted force. The results remain model-dependent and require experimental verification of inerter efficiency, friction, backlash and long-term reliability.

Hashtroudi and Pourzeynali (2023) proposed using selected independent storeys as large distributed tuned masses in a high-rise building. Viscous dampers connect these storeys to the main structural system, enabling both inertial counteraction and energy dissipation. Optimization identified effective installation levels and demonstrated simultaneous reductions in displacement and acceleration for the analysed three-dimensional steel building. The concept is attractive because usable building mass may replace a dedicated roof block, potentially reducing dead-load and space penalties. Conversely, functional floors cannot be treated as mechanically unconstrained masses: serviceability, diaphragm action, utilities, fire separation and vertical circulation become critical. Further work should therefore test constructability and robustness under bidirectional, torsional and nonlinear response.

The second cluster emphasizes nonlinear devices, near-fault pulses, height-wise placement, soil–structure interaction (SSI) and lifecycle robustness. Together these studies explain why nominally similar dampers can yield contradictory outcomes when the excitation spectrum, soil flexibility, response metric or uncertainty model changes. Rajana et al. (2023) optimized a tuned mass damper inerter equipped with a nonlinear viscous damper for seismically excited multi-storey buildings. A power-law velocity model represents realistic nonlinear damping, while analytical approximation and nonlinear response-history analysis are combined to select parameters.

The results indicate that the damping exponent influences absorber stroke and inerter force without producing identical changes in drift and acceleration. This reinforces the need to treat multiple demand measures separately. The framework improves physical realism compared with linear-dashpot designs, but uncertainty in viscous-device properties, temperature effects and connection flexibility can shift the optimum. Experimental characterization is therefore necessary before numerical benefits are translated into design values. Djerouni et al. (2022) assessed tuned mass damper inerter systems under near-fault pulse-like ground motions and optimized their parameters using a genetic algorithm. The study demonstrates that pulse period relative to structural period is a decisive variable: designs effective under broadband or stationary assumptions may become overdamped or inadequately tuned when a strong velocity pulse dominates. The analysis cautions against transferring H2-optimal parameters directly to near-fault applications. Its wider significance is methodological, because record classification and pulse characteristics should enter the design problem rather than being treated as post-design checks. Limitations include dependence on the selected structural idealizations, record set and objective function, together with limited physical validation. Naderpour et al. (2024) studied the level and distribution of tuned mass dampers in reinforced-concrete buildings of different heights. By comparing roof and distributed arrangements, the work indicates that upper-storey placement is generally effective but that multiple devices can improve drift control when higher modes participate. The study connects damper location to acceleration, displacement and maximum inter-storey drift rather than reporting only roof response. It therefore provides useful evidence for multi-criteria placement. Nonetheless, percentage reductions obtained for different heights should not be compared as if they arise from identical dynamic systems. Material nonlinearity, torsional irregularity, uncertainty in cracked stiffness and device stroke must be included before general placement rules are formulated.

Elias and Djerouni (2024) integrated soil-structure interaction into the optimum design of a tuned mass damper inerter for buildings exposed to near-fault pulse-like motions. Their formulation shows that foundation flexibility changes the effective structural frequencies and can detune a device designed from a fixed-base model. The study consequently recommends tuning to the coupled soil-foundation-structure system, especially where soft soil and strong pulse effects coexist. This is a major advance over fixed-base optimization because it identifies a mechanism by which apparently optimal devices lose efficiency. However, soil nonlinearity, foundation uplift, spatial variability and record-to-record uncertainty remain difficult to represent, and field-scale evidence is still required. Matta (2021) compared tuned mass dampers with nonlinear energy sinks using a lifecycle-cost and robustness perspective. The analysis moves beyond peak response by linking control performance to expected seismic consequences and stiffness uncertainty. It finds that robustly designed TMDs can remain competitive with nonlinear absorbers when uncertainty is explicitly included, but the conclusion is not a universal ranking because it depends on hazard, loss model, tuning assumptions and feasible device capacity. The paper's central contribution is to connect structural-control design with economic decision-making. Remaining limitations concern the accuracy of fragility and consequence models, the representation of ageing and maintenance, and the scarcity of full-scale comparative observations.

3. Research Methodology

The present study adopts a systematic review methodology to examine the design, optimization, dynamic performance and practical implementation of Tuned Mass Dampers (TMDs) and hybrid vibration-control systems in high-rise buildings. The methodology is structured according to PRISMA 2020 principles to ensure transparency, reproducibility and methodological consistency.

1) Research Design

This research employs a systematic literature review combined with a critical thematic synthesis. The systematic component provides a structured procedure for identifying, screening and selecting relevant publications. The critical synthesis compares the selected studies according to structural configuration, TMD type, excitation, design variables, analytical method, validation procedure and response-control effectiveness. The review does not treat the uploaded dissertation as primary evidence; it is used only to establish the thematic background and identify relevant structural-response parameters such as storey displacement, inter-storey drift, acceleration and base shear.

2) Search Strategy

A combination of keywords and Boolean operators is used to identify relevant publications. The principal search expression is: ("tuned mass damper" OR "multiple tuned mass damper" OR "pendulum tuned mass damper" OR "particle tuned mass damper" OR "tuned liquid damper" OR "semi-active tuned mass damper" OR "active tuned mass damper" OR "tuned mass damper inerter" OR "nonlinear energy sink" OR "hybrid vibration control") AND ("high-rise building" OR "tall building" OR "multi-storey building" OR "reinforced concrete building" OR "steel building") AND ("seismic response" OR earthquake OR wind OR "near-fault motion" OR "structural vibration" OR "base isolation").

The search expression may be modified according to the syntax of each database. Searches are conducted in article titles, abstracts and keywords.

3) Inclusion Criteria

A study is included when it satisfies the following conditions:

- It is a peer-reviewed journal article or a technically substantial review article.
- It is written in English.
- It investigates a TMD, MTMD, TMDI, active or semi-active TMD, tuned liquid or particle damper, nonlinear energy sink, base-isolated system or hybrid control arrangement.
- It considers high-rise, tall, multi-storey or dynamically comparable building structures.
- It clearly describes the structural model and vibration-control configuration.
- It reports at least one response parameter, such as displacement, drift, acceleration, base shear, damping, energy dissipation or damper stroke.

- It employs analytical, numerical, experimental or full-scale validation methods.
- Its bibliographic details and DOI or publisher record can be verified.

4) Exclusion Criteria

The following publications are excluded:

- Non-peer-reviewed blogs, commercial websites and unsupported technical notes.
- Conference abstracts without sufficient methodological information.
- Studies dealing exclusively with vehicles, machines, bridges or rotating equipment without relevance to building vibration control.
- Articles that do not define TMD properties or structural-response parameters.
- Duplicate publications or repeated versions of the same study.
- Retracted, inaccessible or bibliographically unverifiable publications.
- Studies that provide only general descriptions without analytical, numerical or experimental evidence.
- Articles written in languages other than English.

5) Study Screening Procedure

The screening process is performed in four stages. First, all records retrieved from the selected databases are compiled in reference-management software such as Zotero. Second, duplicate records are removed using DOI, title and author matching, followed by manual checking. Third, titles and abstracts are screened against the eligibility criteria. Finally, the full texts of potentially relevant studies are assessed. Reasons for full-text exclusion are recorded, such as inappropriate structural application, insufficient methodology or absence of measurable outcomes. The final selection process is presented using a PRISMA flow diagram. Numerical PRISMA values must be entered only after the actual database search and must not be estimated.

6) Quality Assessment

Each included study is evaluated using a structured quality-assessment framework. The quality assessment evaluated the clarity of structural models, completeness of TMD parameters, loading descriptions, and suitability of analytical methods. It also examined structural nonlinearity, soil–structure interaction, optimization transparency, numerical or experimental validation, methodological reproducibility, uncertainty and detuning treatment, practical applicability, and explicit reporting of limitations. These criteria ensured consistent appraisal of the reliability, rigor, and relevance of each study.

Each criterion may be scored as 0 for absent, 1 for partially reported and 2 for adequately reported. Studies are not ranked solely according to model complexity because a complex numerical model without validation may provide weaker evidence than a well-controlled experiment.

7) Data Extraction

A standardized data-extraction form was developed to ensure that information from all selected studies was collected consistently and systematically. The extracted information included the author names, publication year, country of origin or institutional affiliation, structural material, number of storeys, and regular or irregular building configuration. Technical details concerning the vibration-control system were recorded, including the type and installation location of the tuned mass damper (TMD), mass ratio, frequency ratio, damping ratio, and other relevant design parameters. The type of excitation, ground-motion characteristics, analytical software, experimental arrangement, and linear or nonlinear modelling assumptions were also documented. Particular attention was given to whether soil–structure interaction, structural uncertainty, and detuning effects were considered. For optimization-based studies, the optimization technique, design variables, constraints, and objective functions were extracted. The reported response parameters, such as displacement, inter-storey drift, acceleration, base shear, damper stroke, control force, and energy dissipation, were recorded for comparative assessment. Finally, the principal findings, validation methods, practical implications, and limitations reported in each study were documented to support a transparent, reproducible, and technically consistent synthesis of the available evidence.

8) Eligibility and quality assessment

Eligible records are peer-reviewed English-language journal articles or substantial reviews that analyse a TMD or a clearly coupled hybrid vibration-control system in a building, tall-building benchmark, or a model whose mechanics are directly transferable to buildings. A study must define the primary structure, damper configuration, excitation and at least one structural-response quantity. Blogs, unsupported abstracts, predatory or unverifiable outlets, machine-only applications and records with insufficient methodological detail are excluded. Seminal pre-2015 papers may be retained only when they establish theory that cannot be explained adequately from recent sources. Quality is judged across model clarity, completeness of TMD parameters, excitation definition, validation, treatment of nonlinearity and uncertainty, optimization transparency, reproducibility and practical applicability. Each domain can be rated as absent, partial or complete. A sophisticated numerical model is not automatically high-quality evidence: a study that omits record selection, parameter bounds, convergence or independent validation has limited reproducibility. Conversely, a focused experimental study may provide strong evidence for device behaviour even when its structural model is relatively simple.

9) Evidence Synthesis and Comparison

The extracted evidence is synthesized narratively and thematically. Studies are grouped into conventional TMDs, MTMDs, pendulum and particle dampers, tuned liquid dampers, active and semi-active systems, TMDI/TVMD systems, nonlinear energy sinks, base isolation and hybrid systems. Separate comparisons are undertaken for seismic, wind and near-fault loading.

Percentage reductions are reported only when the uncontrolled and controlled models belong to the same study. Reduction values from different building heights, ground motions or modelling assumptions are not directly compared without qualification. Contradictory findings are interpreted according to excitation frequency, structural height, mode participation, mass ratio, optimization objective, nonlinearity, SSI and detuning.

10) Reliability and Ethical Considerations

Reliability is maintained through transparent search strings, predefined criteria, structured extraction and DOI verification. All technical findings are attributed to their original sources. No references, numerical results, PRISMA counts or experimental findings are fabricated. The review uses published secondary evidence and therefore does not involve human participants, confidential information or primary experimental data. This methodology provides a technically rigorous foundation for evaluating existing TMD systems and identifying future directions for resilient high-rise buildings.

4. Theoretical Foundations

For a primary single-degree-of-freedom structure with displacement x_s and an attached TMD with displacement x_t under ground acceleration $\ddot{u}g$, the coupled equations are:

$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s + c_t(\dot{x}_s-\dot{x}_t) + k_t(x_s-x_t) = -m_s\ddot{u}g$$

$$m_t\ddot{x}_t + c_t(\dot{x}_t-\dot{x}_s) + k_t(x_t-x_s) = -m_t\ddot{u}g$$

The key non-dimensional variables are mass ratio $\mu=m_t/m_s$, tuning ratio $f=\omega_t/\omega_s$, and TMD damping ratio $\xi_t=c_t/(2m_t\omega_t)$, where $\omega_t=\sqrt{(k_t/m_t)}$. Closed-form tuning offers a baseline for linear narrow-band response, but multi-degree-of-freedom buildings require modal effective mass and participation. Under nonlinearity or SSI, the target frequency becomes amplitude- and state-dependent.

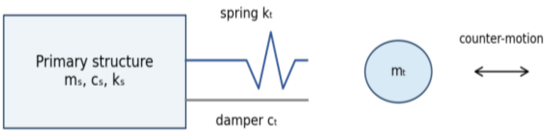

Figure 2: Conceptual working mechanism of a conventional TMD.

Table 1: Influence of TMD design parameters.

Variable	Primary influence	Trade-off / failure mode
Mass ratio μ	Control authority and bandwidth	Dead load, space and cost
Tuning ratio f	Alignment with target mode	Sensitive to stiffness change and SSI
Damping ratio ξ_t	Controls resonance peaks	Excess damping can weaken tuned action
Location	Coupling through modal ordinate	Roof may not control higher/torsional modes
Number of devices	Multi-mode coverage and redundancy	More hardware and maintenance
Stroke capacity	Prevents impact and saturation	Large clearances and restraints required

Detuning, robustness and response selectivity

Detuning is not a binary failure but a redistribution of performance across frequency. A design optimized for roof displacement may provide weaker acceleration or base-shear control because those outputs weight modes differently. Increasing damping broadens the response valley but may reduce peak tuned interaction; increasing mass improves authority but raises force, stroke and architectural burden. Robust design therefore evaluates intervals of structural frequency, damping, device properties and excitation characteristics, rather than reporting one optimum parameter set.

Coupled influence of design variables

Mass, tuning, damping and placement should be interpreted as a coupled parameter set. Increasing auxiliary mass generally strengthens modal interaction, but also increases gravity load, support demand and cost. Moving a device away from a modal antinode can negate that benefit. A wider damping bandwidth may improve robustness to frequency uncertainty while reducing the sharp optimum attainable under a perfectly known linear model. For tall buildings with closely spaced modes, torsion or changing stiffness, the design space should include multiple devices, multidirectional response and explicit stroke constraints.

Response selectivity is equally important. Displacement-oriented tuning does not necessarily minimize acceleration, because acceleration is more sensitive to higher-frequency content. Base shear can fall through period shift even when local drift remains significant, while strong control at the roof may redistribute drift to lower storeys. Multi-objective assessment should therefore retain roof displacement, maximum inter-storey drift, peak and RMS acceleration, base shear, damper stroke and connection force as separate outputs.

5. Classification of Vibration-Control Systems

Table 2: Comparison of conventional and advanced TMD systems.

System	Mechanism	Strength	Primary constraint
Conventional TMD	Single tuned oscillator	Simple, passive, mature	Narrow-band detuning
MTMD	Several frequencies/locations	Bandwidth and mode coverage	Coordination and maintenance
Pendulum TMD	Gravity restoring force	Long period; multidirectional	Stroke and support geometry
Particle TMD	Impact/friction dissipation	Amplitude robustness	Noise, wear, nonlinear calibration
Tuned liquid damper	Sloshing energy dissipation	Water mass can be multifunctional	Free-surface nonlinearity and leakage
Semi-active TMD	Variable damping/ stiffness	Adaptive with low power	Sensors, controller and fail-safe
TMDI/TVMD	Apparent mass amplification	Reduced physical mass potential	High force, friction and backlash
NES	Nonlinear targeted energy transfer	Broadband potential	Activation threshold and predictability
Base isolation–TMD	Period shift plus tuned absorption	Multi-response opportunity	Isolation displacement and integration

Passive systems remain compelling where reliability and low operational demand dominate. MTMDs trade simplicity for modal bandwidth; pendulum and liquid devices suit long-period buildings but require geometric and fluid-service allowances. Semi-active systems adapt to changing response without the energy demand of fully active control, yet their performance depends on sensing and control integrity. Inerters create high apparent inertia but introduce control-force and mechanical-detailing questions. Base isolation shifts the fundamental period and filters high-frequency input, whereas a TMD acts through resonance interaction; their combination is complementary only when isolation displacement, superstructure acceleration and device stroke are jointly optimized.

Selection logic

The system should be chosen from the hazard and response objective rather than from novelty. A conventional passive TMD is suitable when one stable mode governs and uninterrupted reliability is critical. MTMDs are preferable when modal frequencies are clustered or uncertain, provided that additional installation and maintenance can be accepted. Pendulum and liquid systems suit long fundamental periods but require geometric clearance and attention to nonlinear motion. Semi-active control becomes attractive when response characteristics change over time, although its sensors, controller, power supply and fail-safe state must be verified.

TMDI and TVMD concepts are relevant where physical mass is restricted, yet apparent-mass amplification does not eliminate force transfer to the structure. A base-isolation–TMD hybrid is justified when isolation displacement and superstructure response must be controlled simultaneously; it should not be selected merely because two devices appear stronger than one. Practical comparison must use the same structural model, earthquake or wind inputs, device-mass accounting, response measures and constraint set.

6. Performance Under Seismic Loading

Far-field motions commonly produce broadband demand, while near-fault records may contain dominant velocity pulses whose period approaches the structural or isolated period. This distinction changes the optimum: a damper tuned using stationary assumptions may perform poorly under a short-duration pulse. Nonlinear yielding further shifts modal properties, so linear-elastic reductions cannot be extrapolated to collapse prevention. For irregular towers, torsional modes and directional coupling require multidirectional or distributed absorbers.

Far-field and near-fault ground motions

Under far-field excitation, the TMD is evaluated across a suite of records whose frequency content, duration and intensity vary. Record-to-record dispersion should be reported because an average reduction can hide cases of ineffective or adverse response. Near-fault records require separate treatment: a dominant velocity pulse can impose a large demand before steady tuned interaction develops. The pulse period relative to the building period, not simply peak ground acceleration, helps explain why a device optimized for broadband excitation may underperform near a fault.

Nonlinearity, irregularity and soil–structure interaction

Inelastic response changes the effective stiffness and damping of the primary structure and therefore the frequency used for tuning. Robust designs should track this shift over multiple intensity levels and should not assume that elastic-service tuning remains optimal near collapse. Plan or vertical irregularity introduces torsion, mode localization and directional dependence, which can make a roof-centred single TMD inadequate. SSI adds another detuning mechanism by lengthening the coupled system period and modifying radiation damping; the damper should be tuned to the soil–foundation–structure system rather than a fixed-base approximation.

Critical interpretation

Response measures must not be collapsed into a single label of ‘seismic performance.’ Roof displacement is related to global sway; peak inter-storey drift controls many structural and non-structural damage mechanisms; acceleration affects contents and comfort; base shear reflects force demand but can be altered by period shift. A TMD may lower roof motion while increasing local acceleration near its attachment or demanding excessive stroke. Similarly, added damping in an isolation system may limit bearing displacement while transferring more acceleration into the superstructure.

The uploaded dissertation’s G+10 comparative model-uncontrolled, base-isolated, roof TMD, and combined base-isolation–TMD- illustrates why direction- and response-specific interpretation is essential. Those numerical values are not treated as systematic-review effect sizes because they arise from one model and are internally inconsistent in some figure narratives versus tables. The tabulated results are best regarded as a thematic case motivating verification, not as external evidence. A publication-grade comparative study would require model validation, time-history record definition, uncertainty analysis and unit consistency.

Contradictory findings

Studies that favour high mass ratios, distributed devices or inerter augmentation do not necessarily conflict. They often optimize different outcomes under different constraints. A high-mass device can strongly reduce drift but be infeasible architecturally; an inerter can reduce physical mass yet increase connection force; distributed dampers can control higher modes but add hardware; robust conventional tuning can outperform nonlinear devices when uncertainty and lifecycle loss are considered. The correct conclusion is conditional superiority within a defined design domain.

7. Performance Under Wind and Multi-Hazard Loading

Wind serviceability is frequently governed by peak or root-mean-square acceleration rather than strength. Along-wind response is driven mainly by turbulence, while across-wind motion can be dominated by vortex shedding and aerodynamic coupling. Because the dominant wind-response frequency may remain close to the first mode for long durations, TMDs are well suited to slender towers; nevertheless, amplitude dependence, torsional motion and changing wind direction demand multidirectional assessment.

Along-wind, across-wind and torsional response

Along-wind vibration is primarily associated with fluctuating drag, whereas across-wind response may be amplified by vortex shedding and aeroelastic interaction. The two components should not be represented by one generic lateral load. A damper tuned to the first sway mode may reduce along-wind RMS acceleration but offer limited control when torsion or a closely spaced across-wind mode dominates. Bidirectional or distributed devices should therefore be considered for asymmetric plans and changing wind direction.

Occupant comfort and validation
Occupant comfort depends on acceleration magnitude, frequency, exposure duration and perception criteria. Reporting only top displacement is insufficient for wind-serviceability design. Wind-tunnel testing remains important for aerodynamic forcing and aeroelastic coupling, while CFD can extend the parameter space when turbulence modelling and pressure predictions are validated. Structural damping used in the wind model must be stated because small changes can substantially alter predicted acceleration and the apparent benefit of a TMD.

Multi-hazard requirements
A TMD designed for frequent wind excitation must also survive rare earthquakes. The required earthquake checks include maximum stroke, impact protection, restraint behaviour, support forces and post-event operability. A semi-active device requires a defined passive fail-safe state during power or communication loss. Multi-hazard design should distinguish everyday comfort, damage limitation and life-safety objectives and should verify that improvement under one hazard does not create unacceptable demand under another.

8. Optimization Approaches

Classical, metaheuristic and multi-objective optimization
Classical closed-form tuning remains valuable for checking an idealized linear SDOF model and for generating initial parameter estimates. Gradient and direct-search methods extend the design to stiffness, damping and placement variables but can converge to local optima when the response surface is non-smooth. Genetic algorithms and differential evolution are widely used for discontinuous placement or nonlinear TMDI problems; their results should be repeated with documented seeds and convergence histories. Multi-objective optimization is preferable when displacement, acceleration, drift, stroke, control force, mass and cost conflict, because the resulting Pareto front exposes engineering trade-offs instead of hiding them in one weighted score.

Robust, reliability-based and surrogate-assisted design
Robust optimization tests performance over bounded variation in structural frequency, damping and device properties. Reliability-based design goes further by assigning probability models to uncertainty and minimizing failure probability or expected loss. Both approaches are more defensible than nominal tuning when cracked stiffness, SSI or ageing is important, but their conclusions depend on the assumed uncertainty distributions. Machine-learning or surrogate models can reduce the cost of repeated nonlinear analyses, provided that the sampling domain, validation error, extrapolation limit and physical constraints are reported.

Optimization is meaningful only when the mathematical objective represents engineering performance. Minimizing one roof displacement under one record can conceal drift concentration, acceleration amplification, force demand or stroke saturation. Multi-objective formulations expose these conflicts using Pareto fronts, while reliability-based approaches consider uncertainty in structural stiffness, device properties and excitation. The preferred workflow combines a transparent reduced model for exploration with nonlinear response-history verification of selected designs.

Reproducibility requirements
A reproducible study should publish parameter bounds, mass definition, damping model, record list and scaling method, random seeds, convergence checks, objective normalization and constraint-handling rules. Surrogate models should report sampling strategy, training/test separation, prediction error and extrapolation limits. Optimization using ETABS, SAP2000, ANSYS, OpenSees or MATLAB should document how modal data, nonlinear elements and device forces are exchanged; naming software alone is not validation.

Decision framework
First identify the governing hazard and performance measure. Second characterize participating modes, frequency uncertainty and SSI. Third screen feasible physical mass, stroke, support force, power and space. Fourth compare passive, distributed, adaptive and hybrid concepts using consistent loads. Fifth optimize multiple responses and lifecycle cost. Finally, verify through nonlinear analysis and an experimental hierarchy progressing from component tests to shake-table, wind-tunnel and full-scale monitoring.

9. Practical Implementation Challenges

Large auxiliary mass affects gravity design, space planning and erection. Long-period devices demand substantial stroke and reliable end stops; supports and connections must resist control forces without introducing local failure. Fluid and particle systems add sealing, corrosion, noise and calibration issues. Semi-active or active control adds sensors, data acquisition, power, cybersecurity and fail-safe requirements. Inerters require attention to friction, backlash, durability and force transfer. Every system needs inspection access, commissioning tests and a retuning strategy.

Whole-life assessment should include construction disruption, replacement intervals, power, maintenance, downtime and consequences of malfunction. A passive system may be favoured where reliability dominates, even if a more complex device offers better nominal response. Conversely, an adaptive system may be justified in a highly flexible tower with uncertain occupancy or multi-hazard demand. Procurement and code acceptance require clearly defined design actions, redundancy, proof testing and monitoring criteria.

Figure 3: Future research roadmap.

10. Conclusions

This review shows that TMD performance is conditional rather than universal. Conventional passive devices provide mature and power-independent control when the target mode is stable. Multiple dampers improve bandwidth and mode coverage; semi-active systems adapt to changing states; inerter-based devices can amplify apparent mass; and base-isolation hybrids can distribute control between foundation and superstructure. Each benefit introduces a corresponding penalty in mass, stroke, force, complexity, reliability or maintenance.

The most consistent design lesson is to align the device with the governing response and hazard. Mass, tuning and damping ratios, height-wise placement, structural nonlinearity, soil flexibility and uncertainty interact. Consequently, reductions from incompatible models must not be pooled without normalization. The literature is strongest in numerical optimization and weakest in comparable experiments, full-scale monitoring and long-term economic evidence.

Future research should use transparent multi-objective formulations, nonlinear SSI-aware models, uncertainty quantification and lifecycle metrics, followed by component, system and full-scale validation. Digital twins may support identification and retuning, but only when sensor reliability, governance and fail-safe operation are addressed. A practical selection framework should therefore combine structural response, constructability, device capacity, resilience, maintainability and whole-life cost.

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